Logging roads in tropical forests

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Title

Logging roads in tropical forests: Synthesis of literature written in French and English highlights environmental impact reduction through improved engineering

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Abstract

Logging roads are considered important causes of forest degradation due to direct and indirect impacts on ecosystem functioning and biodiversity. Given that logging prevails in tropical forests around the world, effectiveroad management is of crucial importance to reduce logging-related environmental impacts and the costs of logging operations at the same time. In a review we analysed how logging roads are addressed in the literature. We compared studies published over the past 65 years in the journal *Bois et Forêt des Tropiques* (BFT), written mostly in French, with a range of more recent articles from the databases Scopus and Web of Knowledge. Half of the articles on the subject in BFT were published before 1972, while the generalist databases show a steady increase in publication rate since then, reaching its present peak. From the whole body of literature, we selected 126 articles, dealing with impacts and management of logging roads in tropical forests around the world, for critical appraisal. Articles in BFT were characterized by a strong focus on practical issues in forest road engineering, while many publications written in English were focussed on the identification of impacts on forest ecosystems. Road-related environmental impacts stem from the loss of forest cover during their construction, the augmentation of edge effects, soil erosion and interference with wildlife, as well as their facilitation of access to the forest for hunting and agricultural colonization. Based on this review we present a list of recommended measures to reduce these impacts. We conclude that, despite the continuing attention paid to the subject, little is known about the long-term fate of logging roads in the forest landscape.

1. Introduction

Almost half of all remaining tropical forests in the world are subject to selective logging, with 20% having already been logged (Asner *et al.*, 2009) and 400 million ha of natural tropical forests being in the permanent timber production estate (Blaser *et al.*, 2011). Tropical forests are of global importance for carbon storage, biodiversity, food provisioning and other ecosystem services of great value for livelihoods. With less intact tropical forest available, these pivotal functions increasingly need to be delivered by logged forests that can retain high conservation values despite the logging disturbance (Edwards and Laurance, 2013; Rutishauser *et al.*, 2015). However, destructive and poorly planned logging practices persist throughout the tropics (Putz *et al.*, 2000, 2008) and there is an urgent need to better reconcile timber extraction with biodiversity conservation (Putz *et al.*, 2012; Edwards *et al.*, 2014).

Globally road networks have expanded rapidly over the past century, especially in tropical regions in recent years (van der Ree *et al.*, 2015). In production forests roads are the main infrastructure for timber extraction. Historically, in forests adjacent to large enough rivers, rafts of logs were often floated down-river, but this means of transport is decreasingly used because it is slow and subject to a high rate of losses (Wilkie *et al.*, 2000). Due to their spatial extent, construction and maintenance of roads is the most costly component of logging operations (Holmes *et al.*, 2002; Medjibe and Putz, 2012) and also the element of logging in natural forests with the greatest environmental impacts (Mason and Putz, 2001; Laurance *et al.*, 2009). Because roads are the component of logging that is most easily detected, especially by remote sensing (Figure 1), roads are frequently used as inputs for observation and modelling of tropical land use and land cover change (Brandão and Souza, 2006; Laporte *et al.*, 2007; Rosa *et al.*, 2014).

This article is a critical appraisal of the literature on the environmental impact of logging roads on natural tropical forests. Recent years have seen a rapid increase in articles addressing the impacts of roads on forest ecosystems. However, no previous review has adequately covered both the recent literature predominantly written in English and the previous French-language forestry literature, despite the long record of French science on tropical forest road management. We analysed the representation of logging roads in the literature over the long term with a particular focus on the question of how road-related impacts on forest ecosystems can be reduced.

2. Methods

2.1 Literature search

We used fixed search strings to generate search hits and used their number as an indication of coverage of the subject. For the French-language literature, we chose to limit the search to the journal Bois et Forêts des Tropiques (BFT), as it is the main publication for French-language papers on this topic and it has a fully open-access archive dating back to 1947. This extensive archive is not fully covered by any of the common generalist databases and merits an analysis on its own. We used the search engine on the website http://bft.cirad.fr/ which does not accept Boolean operators or wildcards, therefore we successively applied the search strings: “route forestière”, “piste forestière”, “route exploitation” and “piste exploitation”. For comparison we used the two most well-established databases that cover the widest scope of English-language literature, while focussing on peer-reviewed publications, Scopus and ISI Web of Knowledge. Google Scholar is also widely used to search for scientific literature as it also includes grey literature, books and reports. However, due to practical constraints a systematic assessment of this source was not possible and we only used it to select some influential publications outside peer-reviewed journals. In Scopus we used the search strings:

"logging OR forest AND road AND tropic*" and in Web of Knowledge "(logging OR forest) AND road AND tropic*". According to their websites the Scopus archive dates back to 1966 and Web of Knowledge covers articles back to 1900, however these databases are not transparent about the date since when articles from different sources are included. The total number of articles obtained by search hits were 57 for BFT, 656 for Web of Knowledge and 463 for Scopus. The first hit for the search strings in both of the databases covering English-language literature is in the year 1972. By the end of that year, 50% of all the identified articles in BFT had already been published, with a peak in the number of articles on the subject in the early 1950s. In Web of Knowledge and Scopus the subject was covered regularly only from the 1990s onwards, with a steadily increase in the number of articles, reaching almost 60 in Web of Knowledge in 2013 (Figure 2). These results are subject to bias due to the large differences in structure and coverage of the databases *versus* the single journal, BFT, and reflect the total number of papers published. We also emphasize that a wide range of forestry journals, including BFT, are only covered by Web of Science and Scopus from the 1990s onwards, therefore their earlier articles (and those from other professional forestry publications) are excluded from the searches using these two databases. The database CAB direct (http://www.cabdirect.org) has a more comprehensive coverage of the professional forestry literature, but is less used. We conducted a search only for comparison, which produced 704 hits using the same set of keywords as above. For a more systematic approach, a much wider search string would be necessary in order to capture all relevant forestry literature. Using the search string (logging OR forest*) AND (road*) AND (tropic* OR …) and for "…" (adding all tropical countries separated by OR (see Petrokofsky *et al.*, 2015)) generated 2721 results in CAB direct. However, even such an extensive search generates the first hits only for the year 1969, while in the year 2013 alone there were 174. This partly reflects the limited coverage of older publications also in this database (earlier literature is well covered by the publication "*Forestry Abstracts*", but this could not be accessed by our on-line search) but it also shows the increasing number of articles in general, and on this subject in particular.

Notwithstanding these methodological limitations in the search for articles, our results do indicate that researchers publishing in BFT addressed the subject of roads in tropical forests at the earliest stages of the development of the subject. We therefore consider it of great interest to include such publications in a critical appraisal comparing them with the dominant literature accessed by most people who use the common generalist databases such as Web of Knowledge and Scopus.

2.2 Selection of articles

For critical appraisal we selected 19 articles from BFT, 99 from the overall body of English-language peer-reviewed publications plus 5 books and 4 reports from searches in Google Scholar. Articles that addressed logging roads in tropical forests were selected by their relevance for the disciplines ecology, engineering and geography. An overview of the selection criteria that were used for the screening of articles is given in Table I. The term "logging road" is frequently used without further definition. We included only the articles reporting on roads that are built to allow wheeled vehicles to transport harvested logs from the landings, where they are loaded, out of the forest. We excluded roads constructed primarily for public use. The selection therefore includes primary (access) roads, which are mostly build for permanent use, as well as secondary (dead-end) roads, generally built for use over a limited time during a single timber harvesting operation. This definition excludes skid trails designed for use by tracked vehicles, which are narrower and thus often do not form a continuous opening of the canopy. Due to constraints of time and resources, the choice and application of selection criteria were not independently tested by a second person, hence their reproducibility might be limited.

The geographical focus of the articles differed between the two literatures. Whilst the French-language BFT papers were mostly focused on Francophone African countries, a majority of the English-language articles focused on tropical America, in particular the Amazon. Only half as many English-language articles focused on Asia and again fewer on Africa, with a few on tropical Australia (Figure 3).

3. Critical appraisal

3.1 Technical advice for forest exploitation

The very first article in BFT that mentioned roads in Central African forests (Steinmann, 1948), was written with the connotation of adventure in exploring the forest as unknown territory in order to gain access to forest resources in the French colonies. Over the next few years the articles in BFT became very specific in giving technical advice for road planning, building and maintenance in order to ensure efficient logging operations. Detailed descriptions of machines used for construction, maintenance and transport were given (Tuffier, 1954; Le Ray, 1958) but also a wide range of recommendations for road engineering were presented and discussed. Of major importance here was the construction of roads adapted to the landscape, e.g. fitting a road into the terrain, contouring the shape of the road surface, implementing drainage systems and designing river crossings (Allouard, 1954a; Le Ray, 1956, 1960; Esteve and Lepitre, 1972a). Decades later, and without making reference to these articles, several very similar ideas and recommendations were presented in a book in English on forest road operations in the tropics (Sessions, 2007), showing that most of these engineering principles introduced more than 60 years previously are still considered to be "good" practice. Early articles also considered the planning strategy of the overall road network and the optimization of the layout, with maps and schematic plans given as examples (Allouard, 1954b; Krzeszkiewicz, 1959; Le Ray, 1959). The average skidding distance of

1 km in Central Africa, which is the main variable that influences road spacing in the landscape, has not changed since then (*personal observation*). These articles were based on the primarily objective of maximizing the number of trees that can be reached with the least effort and costs for road building. However, they also mentioned that these measures would help to reduce the extent of damage to the forest. For most subsequent articles on this subject, in other journals (e.g. Gullison and Hardner, 1993; Dykstra and Heinrich, 1996; Johns *et al.*, 1996; FAO & ATIBT, 1999; Picard *et al.*, 2006; Schulze and Zweede, 2006), the primary objective changed towards environmental impact reduction, but the recommended practices remained very similar.

3.2 Direct impacts of roads on tropical forests

We found few detailed analyses of the ecological impacts of logging roads in articles published in BFT. Estève (1983) quantified the destruction of forest cover for logging-related infrastructure in Central Africa and South America and concluded that, with only 5% destruction, the ecological value of the forest remained largely unchanged. In an African logging concession, roads and log landing sites accounted for only 0.8% of the forest area (Durrieu de Madron *et al.*, 2000). However, the majority of the English-language articles published over the last 25 years give a strongly contrasting perspective, describing a variety of road-related threats to forest ecosystems with potentially detrimental effects to their ecological functioning at various scales. The amount of forest cover cleared (Figure 4), and thus biomass lost, for road building has been raised as an issue in terms of local-scale impacts (Olander *et al.*, 1998; Gideon Neba *et al.*, 2014). However, strong regional differences are reported, with a notably high average value of 17% stand disturbance by roads and skid trails in Malaysia (Pinard *et al.*, 2000).

Even if only a small proportion of the forest cover is cleared for road building (as in most of Central Africa and Amazonia), negative effects might reach much further. Edge effects can lead to the death of big trees (Laurance, 2000) and the desiccation of forests due to enhanced evapotranspiration in adjacent forest areas (Goosem, 2007; Briant *et al.*, 2010; Fraser, 2014; Kunert *et al.*, 2015). Together with large amounts of debris (left behind after clearing) as a potential fuel, roads can thus increase the vulnerability of the forest to fires (Uhl and Kauffman, 1990; Nepstad *et al.*, 2001).

Road construction drastically changes the forest habitat, not only by removing vegetation but also by altering soil functions through removal of top soil, application of external materials and heavy mechanical compaction (Donagh *et al.*, 2010). The most severe effect of soil exposure and compaction is often erosion (Malmer and Grip, 1990; Douglas, 2003), which in combination with heavy tropical rainfall can remain a problem for more than ten years after logging (Clarke and Walsh, 2006). This results in the loss of soil material on and around roads and the accumulation of sediment in streams and rivers (Gomi *et al.*, 2006; Ziegler *et al.*, 2007; Negishi *et al.*, 2008). Together with other hydrological impacts, e.g. damming of water courses through inadequately constructed river crossings, this can lead to serious deterioration of the ecosystem by changing the physical and chemical characteristics of the water (Trombulak and Frissell, 2000; Bruijnzeel, 2004; Connolly and Pearson, 2007). This can have a direct impact on local communities who depend on the ecosystem service of clean drinking water from streams (Mandle *et al.*, 2015). Many of these articles examining road-related impacts also present possible mitigation measures that we discuss in detail below.

Roads in forests directly interfere with animal populations through road kill (Laurance *et al.*, 2009; Clements *et al.*, 2014) but also by influencing their movement and behaviour (Chazdon *et al.*, 2009; Lees and Peres, 2009; Hoeven, 2010). Negative effects of roads have been shown on small mammals (Malcolm and Ray, 2000), birds (Develey and Stouffer, 2001;

Laurance and Gomez, 2005), elephants (Blake *et al.*, 2008) and dung beetles (Hosaka *et al.*, 2014). This has been associated with habitat changes and human activity, but increased noise levels can also have an impact (Laurance, 2015). However, roadsides and abandoned roads can also attract animals due to higher abundance of herbs as food sources, as has been shown for gorillas (Matthews and Matthews, 2004). Puddles and ditches resulting from compacted soils on logging roads have been reported to be a suitable reproduction site for turtles (Ernst *et al.*, 2014). An overview of the varying effects of roads on different groups of species is given by van Vliet and Nasi (2007) showing, for example, that elephants are more frequently found in proximity to roads and settlements, while certain wild ungulates show strong patterns of road avoidance.

3.3 Indirect impacts of roads on tropical forests

Arguably the biggest threat resulting from logging roads in the tropics is that they grant access to the forest interior for other land uses. The presence of roads facilitates illegal and uncontrolled logging activities (Obidzinski *et al.*, 2007, Laurance and Balmford, 2013) and the probability of logged areas being deforested is highly dependent on distance from major roads (Asner *et al.*, 2006). This is mostly because logging roads are used successively for encroachment by farmers who colonize new areas for slash-and-burn agriculture (Johns *et al.*, 1996; Reid and Bowles, 1997; Mertens and Lambin, 2000; Pfaff *et al.*, 2007). However, this process varies depending on human population density, soil quality and topography (Cropper *et al.*, 1999), as well as market access and tenure regulations (Chomitz and Gray, 1996), and is often linked with official re-designation of roads for public use or even large-scale programs with incentives for colonization (Nepstad *et al.*, 2001; Barber *et al.*, 2014). With increasing disturbance intensity this can lead to feedback loops resulting in deforestation or severe degradation at larger scales (Laurance *et al.*, 2002; Malhi *et al.*, 2014).

In the absence of appropriate landscape planning, over the long-term some roads initially built for logging have developed into major public roads and can even be linked with the conversion to large-scale agro-industrial agriculture and pastoralism. This has been reported for Latin America and South-East Asia for cattle grazing, soy-bean production and oil-palm plantations (Reid and Bowles, 1997; Fearnside, 2007; Laurance and Balmford, 2013). However, the reason why logged forests become vulnerable to such conversions can only indirectly be attributed to the presence of roads. It is more linked with the loss in short-term economic value and a widespread underestimation of the ecological importance of production forests (Gaveau *et al.*, 2013; Edwards *et al.*, 2014).

A less visible form of forest degradation resulting from roads is the depletion of wildlife populations through unregulated hunting that has even resulted in “empty” forests (Redford, 1992; Robinson *et al.*, 1999; Laurance *et al.*, 2006; Poulsen *et al.*, 2011). In Central Africa especially, bushmeat provides the most important source of protein for most forest-dependent communities, making hunting an essential activity for human nutrition that has been practiced for a long time (Figure 5). However, the presence of extensive road networks has led to a process of specialization of market hunters linked to a longer transport chain and increased quantities of extracted bushmeat being supplied to meet the increasing demand in urbanized areas further away from the forest (Wilkie *et al.*, 1992, 2000; Nasi *et al.*, 2008). Even logging vehicles are frequently used to transport hunters, weapons and game, thus increasing the radius of defaunation around settlements deeper into the forest (Poulsen *et al.*, 2009).

Roads can also facilitate biological invasions in tropical forests. Dispersal by trucks and other logging vehicles has been shown to be the main driver for the spread of exotic tree (Padmanaba and Sheil, 2014), ant (Walsh *et al.*, 2004) and grass (Veldman and Putz, 2010) species.

3.4 Reducing the impacts of logging roads

The potential problems with roads in tropical forests have long been appreciated from a forest management perspective (as evidenced in the BFT articles reviewed above) and so there has been a parallel set of publications focused on the development of engineering techniques designed to minimise these problems. These are well represented in both the French- and English-language literatures (Table II).

Improved road planning, construction and maintenance has been a central element in the development of reduced-impact logging (RIL) guidelines (Pinard *et al.*, 1995) and in the FAO model code of forest harvesting practice (Dykstra and Heinrich, 1996). Effective road planning in order to reduce residual stand damage and loss of biomass, as described in BFT in the 1950s, was included as a key component of RIL (Putz *et al.*, 2008). Another important recommendation is to reduce the clearing width of road corridors (Sist, 2000). Especially in Central Africa, there is still a widespread belief among forest managers that forest clearing on both sides of the road is necessary to let the sun dry the road surface (Sessions, 2007). However, it has already been emphasized by Allouard (1954b) that a well-maintained and drained road does not require a wide open canopy. Also, the need to build roads fitted to the topography in order to avoid soil erosion on the road surface (Negishi *et al.*, 2008) has long been articulated (Le Ray, 1956).

With a stronger focus on biodiversity conservation, the set of impact-reduction measures has recently been augmented. This includes the declaration of set-asides from logging in high conservation-value areas as well as measures to reduce the fragmenting effect of roads on animal habitats (Goosem, 2007; Clements *et al.*, 2014). Given the problems with hunting and encroachment, control of access has been identified as a crucial aspect of road management. This requires guarded barriers at strategic points in the permanent road network but also the closure of roads after harvest (Mason and Putz, 2001; Applegate *et al.*, 2004; Bicknell *et al.*, 2015). However, wherever local communities do not accept such measures, it becomes difficult for logging operators to enforce them (Figure 6).

Since RIL standards have been published, numerous studies have been carried out comparing the effectiveness of RIL with that of conventional logging, generally emphasizing the usefulness of such measures including road building standards (Healey *et al.*, 2000; Pereira *et al.*, 2002; Feldpausch *et al.*, 2005; Ezzine de Blas and Ruiz Pérez, 2008; Medjibe and Putz, 2012).

Forest regeneration after exploitation is of crucial importance for sustainable forest management (Karsenty and Gourlet-Fleury, 2006; Zimmermann and Kormos, 2012). Given that most secondary logging roads are only temporarily used, they do provide a potential site for tree regeneration after abandonment (Figure 7). However, especially in areas where high volumes of timber are harvested such as the dipterocarp forests of South-East Asia, reduced levels of regeneration have been reported on abandoned roads and skid trails due to unfavourable soil conditions (Pinard *et al.*, 1996, 2000; Zang and Ding, 2009). Also, in more urbanized areas, lower levels of forest recovery have been recorded with proximity to roads (Crk *et al.*, 2009). In contrast, for regions with low intensity logging regimes, logging roads and strip clear cuts have been associated with enhanced levels of regeneration of light-demanding timber species (Hartshorn, 1989; Fredericksen and Mostacedo, 2000; Nabe-Nielsen *et al.*, 2007; Swaine and Agyeman, 2008). Road edges, those areas that have been cleared during road construction to let the sun dry the surface, are particularly suitable microhabitats for recruitment of timber species (Guariguata and Dupuy, 1997; Doucet, 2004).

3.5 Characterizing the spatial distribution and coverage of logging roads

Highly selective logging at low densities, as occurs in most of Central Africa and Amazonia, is a form of cryptic disturbance which, in contrast to full deforestation, can only be detected marginally or not at all with conventional remote sensing techniques on larger scales (Peres *et al.*, 2006). Due to their linearity and connectedness, roads are the only components of such logging activities that are detectable on medium- to high-resolution satellite images. Articles in BFT were among the first to make use of this finding and suggested the use of logging roads as indicators of the extent of logging disturbance in tropical forests (Gond *et al.*, 2003; Mayaux *et al.*, 2003; Bourbier *et al.*, 2013). Despite some technical drawbacks (de Wasseige and Defourny, 2004), it is now the *de facto* standard across all tropical regions to use roads as indicators for human dominance of tropical forests (Asner *et al.*, 2004a, 2004b, 2009; Souza *et al.*, 2005; Laporte *et al.*, 2007; Hirschmugl *et al.*, 2014; Gaveau *et al.*, 2014). The spatial distribution, i.e. the extent and density, of road networks can be used to model human influences on tropical forests at larger scales (Mertens *et al.*, 2001; Arima *et al.*, 2008; Bell *et al.*, 2012; Ahmed *et al.*, 2013b, 2013a, 2014). It also served as an important input to define the intactness of forest landscapes (Potapov *et al.*, 2008) and the identification of priority road-free areas at a global scale (Laurance *et al.*, 2014).

4. Contrasting trends in the literature

Assessment of the literature included in this review reveals two main underlying agendas for these studies that can be roughly classified into conservation approaches *versus* forest management approaches. Dominant parts of the recent literature found in the generalist databases Web of Knowledge and Scopus are focussed on the negative impacts of industrial-type logging and reinforce the long-standing bad reputation of export-driven timber harvesting in tropical countries (Bowles *et al.*, 1998). Only recently, facing the overwhelming occurrence of logging in tropical forests, have publications started to address the ecological value of logged forests that shows the need for them to be protected from further conversion into oil-palm plantations or other agricultural land (e.g. Edwards *et al.* 2011). Conversely, almost all the reviewed articles in BFT adopted a much more pragmatic approach, without openly expressing any doubts about the continuation of logging activities. The history of BFT cannot be disentangled from French colonial history and its’ founding institution, the Centre Technique Forestier Tropical (CTFT). The initial colonial motivation of efficiently organizing forest exploitation in overseas forests was later translated into development cooperation (Bonneuil and Kleiche, 1993). However, no change occurred in the adherence to the traditional principles of sustainable forestry and the aim to promote this in collaboration with a range of stakeholders in the field. Irrespective of the motivations behind the historical literature, it contains a high standard of engineering recommendations and the resulting practices mostly persist to the present day. Knowledge of this historical legacy from the literature is crucial in understanding the development of today’s logging practices. Lessons learned in the 1950s should not be forgotten, but rather fed into modern evaluation and improvement of logging activities.

5. Identification of knowledge gaps

We have reviewed a large body of literature about logging roads in tropical forests, mostly focussing on immediate direct and indirect environmental impacts and on management techniques designed to mitigate these. However, given the history of more than half a century of industrial-scale logging operations it is somewhat surprising that the long-term fate of logging road networks remains unknown, with insufficient attention paid to road abandonment and subsequent forest recovery. This may be linked to the fact that large formerly-logged areas in Latin America and South East Asia are now deforested. However, in Central Africa this is not the case. Here, only a small proportion of logging road networks is maintained in a constantly open state due to the costs and the obligation for many forest concessions to close secondary roads after exploitation. Little is known about the persistence of road networks in the overall forest landscape or about the long-term successional trajectory on abandoned forest roads, especially in Central Africa. Such long-term characterization of forest road networks can help in the development of much needed strategies for post-logging silviculture and should be taken into account when determining forest degradation based on road networks, for example in the context of the REDD+ programme (reducing emissions from deforestation and forest degradation).

We feel that current definitions of intactness or roadlessness of forest landscapes do not do justice to the complexity of the interactions between roads and forests when they are simply based on the application of a fixed buffer distance around all roads. A new understanding of the temporal and spatial dynamics of forest road networks is urgently needed for initiatives that try to reconcile forest certification with the protection of intact forest landscapes. The long-term management of road networks should provide a crucial step towards the anticipated goal of supra-regional landscape planning across the tropics (Lewis *et al.*, 2015).

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Tables

Table I: Inclusion and exclusion criteria for articles to be considered for critical appraisal, listed in hierarchical order.

	Inclusion criteria	Exclusion criteria
Language	English, French (only in *Bois et Forêts des Tropiques*)	Any other language, other journals in the French language
Object	Roads and road networks	
Location	Pan-tropical (Central and South America, Africa, South-East Asia, Australia)	Non-tropical
	Closed canopy tropical forests used for timber exploitation	Tree plantations after clearcutting, woodlands, savannas, wetlands
Principal utilization	Wheeled vehicles transporting timber	Skidding (log yarding), public transportation
Type	Primary roads: permanently maintained, providing principal access to the forest	
	Secondary roads: mostly dead-end roads, connecting logging sites with primary roads, abandoned after use	
Questions and applications	Forest engineering: Layout, design, construction, maintenance, management	Mention roads only as one of many factors in connection with forest degradation and deforestation
	Ecology: interactions with wildlife and forest ecosystems, direct and indirect impacts, persistence, impact reduction	Logging impacts that are not directly linked with roads (e.g. timber species population and recruitment issues)
	GIS and remote sensing: detection, characterization, spatial distribution	Purely concerning economic and social development or land use policy

Table II: Logging-road-related environmental problems and measures to mitigate such impacts. Each measure is only listed once, although it could also be useful in the context of other problems. A selection of the most relevant references is given for each measure.

Road-related environmental problems	**Measures to reduce impacts**	**References**
Forest clearing for road construction (carbon emissions, loss of habitat)	Minimize road length by optimizing the layout (to reach the resource via the shortest path)	Le Ray, 1959; Gullison and Hardner, 1993; Johns *et al.*, 1996; Picard *et al.*, 2006; Schulze and Zweede, 2006
	Minimize road length by finding the optimal ratio between lengths of roads and skid trails	Krzeszkiewicz, 1959; Dykstra and Heinrich, 1996; Sessions, 2007
	No road construction in high conservation-value areas	Sist *et al.*, 1998; Healey *et al.*, 2000; Durrieu De Madron *et al.*, 2011
	Allow changes in road alignment to avoid large trees	Le Ray, 1959; Sessions, 2007
Edge effects: desiccation, wind exposure, death of large trees	Reduce the width of forest clearing for road construction (on average 10 m, taking solar angle and exposure to wind into account)	Allouard, 1954b; Dykstra and Heinrich, 1996; Sist, 2000; Laurance and Gomez, 2005; Feldpausch *et al.*, 2005; Laurance *et al.*, 2009
Soil erosion (and the deterioration of water quality through sedimentation)	Adapt road routing to the topography (location on top of ridges and across slopes)	Allouard, 1954a; Le Ray, 1956; Esteve and Lepitre, 1972b; Pinard *et al.*, 1995; Dykstra and Heinrich, 1996
	Limit the road gradient and the length of downhill runs	Allouard, 1954b; Le Ray, 1956; Sessions, 2007; Ziegler *et al.*, 2007; Negishi *et al.*, 2008
	Ensure drainage through road camber, roadside ditches and cross-drains	Allouard, 1954b; Le Ray, 1956; Dykstra and Heinrich, 1996; Sist *et al.*, 1998; Sessions, 2007; Putz *et al.*, 2008
	Stabilize the road surface with laterite	Allouard, 1954a; Sessions, 2007
	Fitting road alignment to the terrain and good engineering practice to protect slopes (e.g. minimise high risk excavations of side slopes, and stabilise excavations where they cannot be avoided)	Allouard, 1954a; Le Ray, 1956; Dykstra and Heinrich, 1996; Sessions, 2007

Road-related environmental problems	**Measures to reduce impacts**	**References**
Physical alteration of streams	Limit amount of stream crossings	Le Ray, 1959; Clarke and Walsh, 2006
	Apply good engineering practice in building culverts, bridges and fords	Allouard, 1954a; Douglas, 2003; Sessions, 2007
	Place buffer zones around streams and wetlands	Pinard *et al.*, 1995; Sist *et al.*, 1998; Applegate *et al.*, 2004
Road kill and behaviour change of animals	Set and control speed limits	Allouard, 1954b; Laurance *et al.*, 2006, 2009; Sessions, 2007
	Ensure overhead canopy connections (green bridges)	Goosem, 2007; Sessions, 2007
	Set up road crossing infrastructure (signs, speed bumps, bridges, culverts)	Laurance *et al.*, 2009; Clements *et al.*, 2014
	Respect habitats of endangered species in road planning	van Vliet and Nasi, 2007; Clements *et al.*, 2014
	Limit number and weight of logging vehicles	Allouard, 1954b; Sessions, 2007
	Adapt roadside vegetation to animal preferences	Hoeven, 2010
Facilitation of hunting	Control access to currently used roads	Mason and Putz, 2001; van Vliet and Nasi, 2007; Edwards *et al.*, 2014b
	Close secondary roads after harvest with physical barriers and removal of stream crossings	Sist *et al.*, 1998; Applegate *et al.*, 2004; van Vliet and Nasi, 2007; Bicknell *et al.*, 2015a
	Prohibit the transport of hunters and bushmeat with logging vehicles	Robinson *et al.*, 1999; Wilkie *et al.*, 2000; Poulsen *et al.*, 2009
Agricultural colonization	Plan and regulate land-uses, provide alternatives for settlers	Dykstra and Heinrich, 1996; Chomitz and Gray, 1996; Mertens and Lambin, 2000; Laurance *et al.*, 2014

Figures

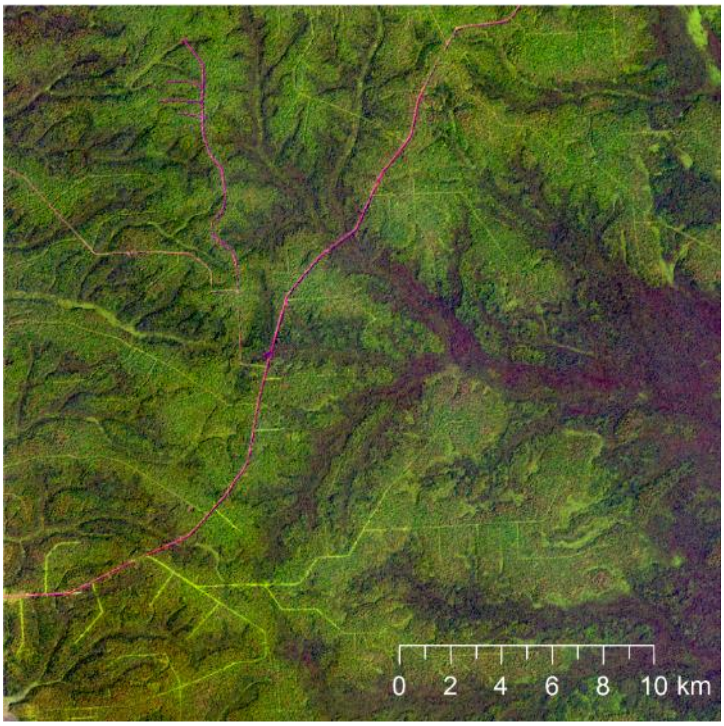

Figure 1. Logging roads in the Northern Republic of Congo. Red colour indicates bare soils as on currently used roads; bright green indicates high photosynthetic activity as on abandoned roads with recovering vegetation. Extract of a LANDSAT 8 image, dated 7th January 2015.

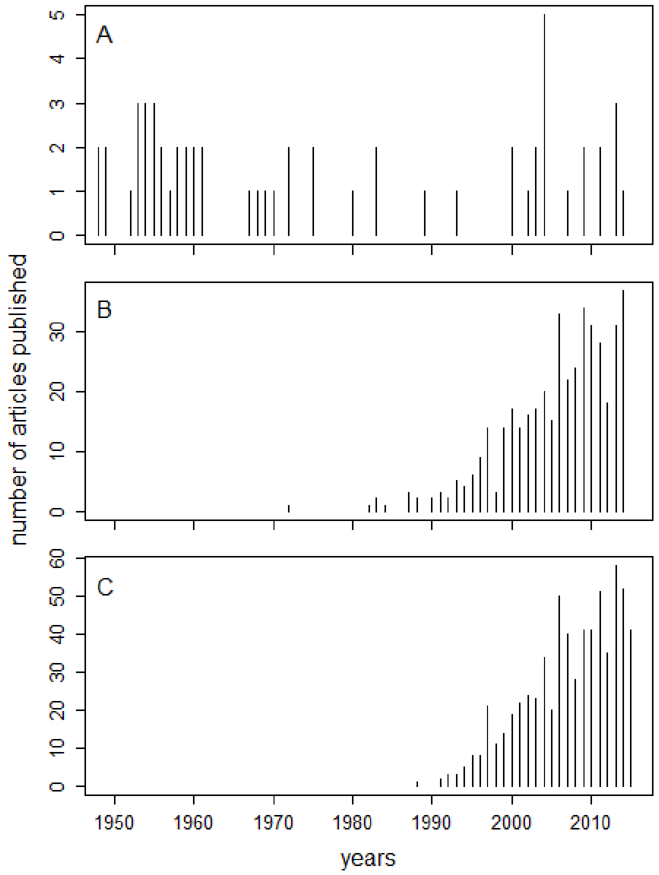

Figure 2: Number of articles obtained by search hits for logging roads in tropical forests (exact search strings are given in the text) in the databases of (A) *Bois et Forêts des Tropiques*, (B) Scopus and (C) ISI Web of Knowledge.

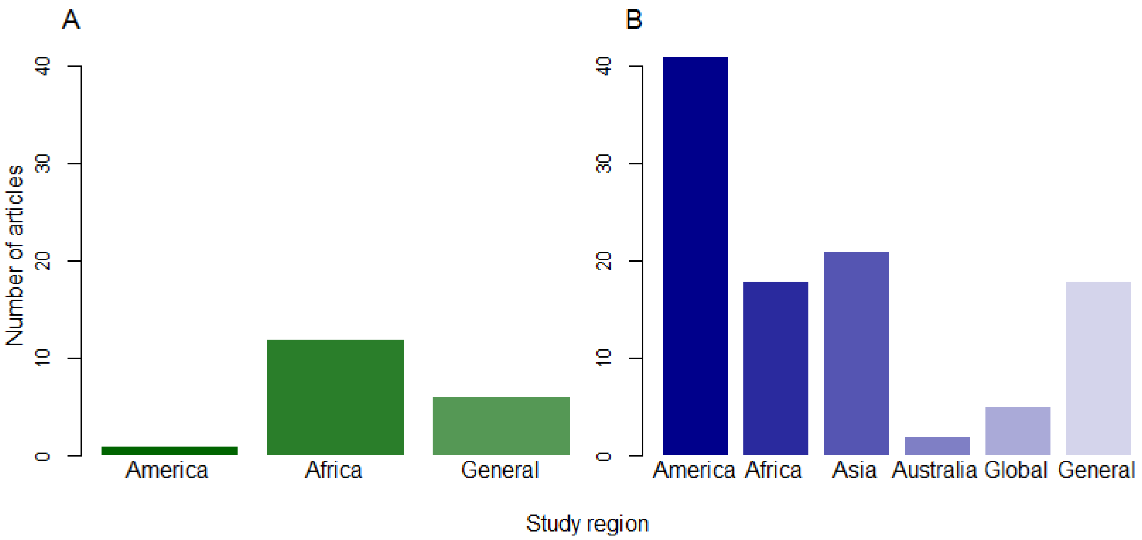

Figure 3. Regional focus of articles (number of articles per continent, if applicable) selected for critical appraisal, comparing articles in *Bois et Forêt des Tropiques* (A) with the English language literature (B). Global = Analyses carried out on a pantropical or global scale, General = General relevance without specific geographical reference.

Figure 4. Newly constructed logging roads in south east Cameroon and northern Republic of Congo. Left: Primary road making permanent access to the forest. Right: secondary (dead-end) road built for temporary use to collect timber from log landings (here stored on the road side).

Figure. 5. Hunted duiker along a logging road in Cameroon.

Figure 6: Attempts to control access to the logging road network in a forest concession in Cameroon. Left: Guarded barrier at the forest edge. Right: Logs placed on a secondary road after harvest to block the access have been burned by hunters to gain access by motorcycle.

Figure 7. Abandoned logging roads, closed with a log to block access one year after exploitation in south east Cameroon (left) and with dense herb cover and regenerating trees 14 years after abandonment in northern Republic of Congo (right).